PERSPECTIVES: MARTIAN CLIMATE

A Message from Warmer Times

Matthew P. Golombek

When the Sojourner rover crawled over the Pathfinder landing site on Mars last year, the images ~~it~~ returned indicated that the site had changed little from when it was created by catastrophic floods some 3.5 to 1.8 billion years (Ga) ago (*1, 2*). This observation provides quantitative constraints on the rate of change at the landing site since that time. The Pathfinder data, taken together with those from the recent Global Surveyor missions and from ~~20 years of~~ the Viking missions, suggest an early warmer and wetter environment with vastly different erosion rates and a major climatic change on Mars between then and now.

The Pathfinder mission was the first to obtain direct data at a small scale. Remote sensing from Viking spacecraft has provided images of the area where Pathfinder landed[JU1], at a scale of a kilometer or greater. Comparison of these images, such as the image of the Ephrata Fan of the Channeled Scabland[JU2] (*3*), with an Earth analog suggests that this region on Mars is covered with streamlined hills; a ridge-trough rocky surface; perched, overlapping, and partially rounded tabular rocks; and a surface analogous to catastrophically deposited fans on Earth. These features are consistent with the ones observed by Pathfinder and indicate that the site has been altered little since it formed about 3.6 to 1.8 Ga ago (*1, 3–5*).

Pathfinder observed a rocky terrain composed of ridges and troughs, perched, partially rounded tabular, ~~rocks~~ and inclined and stacked rocks, and streamlined hills that is analogous to catastrophically deposited FANS fans on Earth, such as the Ephrata Fan in Washington State (1-4).

Erosional features such as an exposed former soil horizon, sculpted wind tails, dunes and other ripple-like lag deposits[JU4] (see figure), and ventifacts (stones worn by windblown sands) are abundant at the Pathfinder landing site, suggesting that the site has undergone net deflation or loss of material (*2, 6*). The 5- to 7-cm-thick redder band along the base of several rocks, interpreted to be a deflated soil horizon, and the sculpted erosional wind tails behind rocks that are less than 3 ~~15~~ cm high (*2, 6*) suggest extremely low deflation rates, of around 0.01 to 0.08 nanometers (1 nm = 10^{-9} m) per year. The ripple-like features and at least some of the dunes, such as Mermaid Dune, appear to be composed of poorly sorted material beneath an armoring veneer of dark gray granules, as could be seen in the trenches created by the rover[JU5]. These have been interpreted as lag deposits (*7*), also indicative of net erosion or deflation of the landing site. The presence of fluted and grooved rocks also argues for erosion by discontinuous flow [JU6]of crystalline sand-size particles carried by the wind (*8*). In contrast, wind-driven deposition at the Pathfinder site is limited to a few dunes, including a barcan[JU7]-shaped feature imaged by the rover that strongly argues for formation from saltating [JU8]sand-size grains (*6*). The unfinished nature of the ventifacts and their different orientation from other wind-driven features has led to the suggestion that the dunes may have formed earlier when the supply of sand-size particles was greater [JU9](*8*). The small number of the dunes, which are less than 15 cm high, suggests that they are the result of redistribution of predominantly locally derived sand-size material at comparatively [JU10]slow rates of less than 0.08 nm per year.

Taken together, these rate estimates for the different features at the Pathfinder site severely limit the overall erosion or deflation of materials to less than 0.1 nm per year (or m/Ga) over the past 3.5 to 1.8 Ga. The rim heights of small craters at the site are similar to those expected for fresh Martian craters. This places similar (<1 nm/year), albeit less precise, constraints on erosion rates at the Pathfinder (*9*) and the Viking 1 [JU11]landing sites (*10*) and suggests that a cold and dry environment, similar to today's, has prevailed since that time[JU12].

A variety of observations by Pathfinder indicate that the earlier Martian climate was warmer and wetter than today's desiccating environment. Rounded pebbles and cobbles (*7*), evidence for abundant sand-size particles (*6*), and possible conglomerates (*7*) at the Pathfinder landing site suggest an early fluvial environment with relatively abundant liquid water. Airborne dust particles collected by the Pathfinder magnetic targets further support this hypothesis (*11*). The particles are composite silicates containing a highly magnetic mineral interpreted to be maghemite. This mineral may have freeze-dried as a stain or cement from liquid water that had previously leached iron from crustal materials in an active hydrologic cycle. Pathfinder detected sand-size particles at the landing site, whereas none could be seen in lower resolution Viking images[JU13]. The Pathfinder data suggest that sand-size particles may be abundant on Mars, a conclusion[JU14]consistent with recent Mars orbiter camera high-resolution images [JU15]returned by Mars Global Surveyor (*12*). On Earth, sand typically forms via water-dominated weathering, erosional and depositional processes that mechanically break down rocks into smaller fragments (*13*), which may be another indicator of a warmer and wetter past on Mars.

The suggestion that the early Martian environment was warmer and wetter is not new [see, for example, (*14*)]. Valley networks (at least one of which, Nanedi Vallis, shows a central fluvial channel in high-resolution MOC[JU16] images, presumably formed by running water) and associated dry lake beds (*14*); possible shore lines, beaches, and terraces inferring a northern ocean (*15*); and rimless, degraded craters in ancient heavily cratered terrain (*16, 17*) have all been described in Viking orbiter images and used to argue for a warmer and wetter past in which liquid water was an integral part of the environment. Erosion rates calculated from changes in crater number and shape formed at x to y years before present [JU17]are 3 to 5 orders of magnitude higher (0.1 to 10 μm/year) than those calculated for more recent times, and are comparable to those in some alpine and periglacial environments on Earth (*16, 18*).

Our knowledge of the Martian surface layer developed from remote sensing observations, image analysis, and observations at the three landing sites [JU18]agrees with the very slow erosion rates described above and suggests that since the Hesperian [JU19], a surface layer with a thickness of up to several tens of meters has been redistributed around Mars (*19*). This layer likely consists of sand- and dust-sized particles that are collected and transported by the wind (*20*). Dust can be deposited and

The author is at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, E-mail: mgolombek@jpl.nasa.gov

removed at much greater rates than sand over short time periods[JU20]. For example, deposition of dust on Pathfinder's solar panels during the 3 months of the mission has been estimated at roughly 20 μm/year (*7, 21*). But this value cannot represent long-term averages, as such high rates would result in the accumulation of meters of dust within a comparatively short span of a million years. However, there seem to be other areas that are net sinks for this material. For example, Amazonis Planitia's thermal inertia, radar, and imaging properties suggest that this is an area with dust accumulations several meters in thickness (*19*). The large region of sand dunes surrounding the polar cap may be another sink (*20*). In contrast, areas such as the Pathfinder landing site appear to have been swept clean or even deflated. These [JU21]short-term rates of deposition and removal and longer term redistribution rates in Late Hesperian and Amazonian time [JU22]are on the order of nanometers per year, comparable in magnitude to erosion rates in the Noachian[JU23].

All these data seem to point to a significant climatic change at some time in the past, but when this occurred is not tightly constrained because of the uncertainties in the proposed crater density time scales[JU24] (*5*). All three landings were in areas of Early Amazonian to Middle Hesperian age [JU25]and thus document the present-day dry, desiccating environment since 3.1 to 3.7 Ga. In contrast, valley networks appear to be dominantly >3.5 to 3.8 Ga in age (*14*). The impact degradation of many valley networks further suggests that they may have formed at the tail end of heavy bombardment around 3.9 Ga (*22*). Future missions to Mars, especially in areas that are sinks for dust material, should give further clues about past climate change on Mars[JU26].

References and Notes

1. M. P. Golombek *et al., Science* 278, 1743 (1997).
2. P. H. Smith *et al., ibid.*, p. 1758.
3. M. P. Golombek R. A. Cook H. J. Moore T. J. Parker, *J. Geophys. Res.* 102, 3967 (1997).
4. M. P. Golombek *et al., J. Geophys. Res. Planets,* in press.
5. Crater time scales are discussed in K. L. Tanaka, *Proc. Lunar Planet. Sci. Conf.* 17, [AU27]*J. Geophys. Res.* 91, E139 (1986).
6. R. Greeley *et al., J. Geophys. Res. Planets,* in press.[AU28]
7. Rover Team, *Science* 278, 1765 (1997).
8. N. T. Bridges *et al., J. Geophys. Res. Planets,* in press.
9. Big and Little craters [JU29]in view of the lander [JU30]have rim heights of 40 m and 5.2 m, respectively, similar to the expected heights (56 m and 6 m) for fresh Martian craters with diameters of 1.5 km and 0.15 km [R. J. Pike and P. A. Davis, *Lunar Planet. Sci.* XV, 645 (1984)]. The differences between the measured and expected heights of these craters are not statistically distinct, given the measured dispersion of fresh Martian crater rim heights. There may thus have been no erosion of their rims. If the craters are not significantly younger than the surface, this limits erosion at the Pathfinder site to <1 nm/year. Although higher erosion rates are possible if the craters are much younger than the surface, they are not argued for by the freshness of the craters[JU31].
10. R. Arvidson, E. Guiness, S. Lee, *Nature* 278, 533 (1979).
11. S. F. Hviid *et al., Science* 278, 1768 (1997).
12. M. C. Malin *et al., ibid.* 279, 1681 (1998).
13. P. H. Kuenen, *Sci. Am.* 202, 94 (1960); D. H. Krinsley and I. J. Smalley, *Am. Sci.* 60, 286 (1972); F. J. Pettijohn, P. E. Potter, R. Siever, *Sand and Sandstone* (Springer-Verlag, CITY, 1987).
14. M. H. Carr, *Water on Mars* (Oxford Univ. Press, CITY, 1996).
15. T. J. Parker *et al., J. Geophys. Res.* 98, 11061 (1993).
16. R. A. Craddock and T. A. Maxwell, *ibid.*, p. 3453; —, A. D. Howard, *ibid.* 102, 13321 (1997).
17. N. G. Barlow, *ibid.* 100, 23307 (1995); J. A. Grant and P. H. Schultz, *ibid.* 98, 11025 (1993).
18. M. H. Carr, *Lunar Planet. Sci.* XXIII, 205 (1992).
19. P. R. Christensen and H. J. Moore, in *Mars*, H. H. Kieffer *et al.*, Eds. (Univ. Ariz. Press, CITY ,1992), pp. 686–729.
20. R. Greeley, N. Lancaster, S. Lee, P. Thomas, *ibid.*, pp. 730–766.
21. G. A. Landis and P. P. Jenkins, *EOS* 79, F549 (1998).
22. V. R. Baker and J. B. Partridge, *J. Geophys. Res.* 91, 3561 (1986).

23. I thank N. Bridges, R. Craddock, R. Greeley, and T. Parker for helpful suggestions and comments and J. Maki for exceptional image processing of the figure. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.

When Mars was wet. Mosaic of the Mars Pathfinder landing site and the Sojourner Rover acquired in the late afternoon of sol 2[JU32]. The low sun emphasizes the bright wind tails behind rocks such as Barnacle Bill and others immediately to the left of the rover. The sculpted appearance of these wind tails suggests that they are dominantly erosional forms. The pebbly surface on which the rover sits and the dark areas to the right of the rover are interpreted as a lag deposit in which finer grained particles have been removed by the wind.

J. MAKI (JET PROPULSION LABORATORY)[JU33]